VENTILATION RESEARCH GOES WITH THE FLOW

How can air quality in office environments be improved when conventional air conditioning systems typically spread pollution throughout the room and create uncomfortable draughts? The answer could be upward plug flow ventilation systems, which carry impurities to the top of the room, leaving clean air around the room's occupants, and which do not cause draughts. HAROLD G. BURNLEY, JR. and LEONARD W. LIPSCOMB report on research that compared the two methods.

Scientists have been searching for a method of air-conditioning that is better than conventional systems at reducing impurities in a room without making the occupants feel uncomfortable.

Such a system could be developed commercially for use in offices and shops, to improve people's working environment.

AIR CONDITIONING

Conventional air-conditioning systems draw in air from outside the building, condition it to the required temperature and humidity, and introduce it into rooms through ceiling diffusers. A return air duct, also located in the ceiling, expels an equal amount of air. This results in a 'mixed room', throughout which contaminants are equally concentrated.

Substantially better air quality can be obtained, according to the findings of scientific research, from an alternative air-conditioning system called upward plug flow ventilation.

Such a system is described in a paper entitled *Design and Application of an Upward Plug Flow Ventilation System*. The paper, presented at the 1993 CORESTA conference, described how researchers developed, evaluated and produced commercially a heating, ventilation and air conditioning (HVAC) system (see Figure 1) that introduces air to the room below a raised floor made with perforated metal plates and covered with a porous carpet. A uniform, upward 'plug flow' of air sweeps contaminants toward a ceiling plenum, through which part of the air is propelled to the outside. The remaining air is cleaned electronically, and particulate and certain gas phase components are filtered out through acid-treated activated carbon. The treated air is then mixed with outside air, conditioned with conventional heating and cooling coils to adjust its temperature and humidity, and introduced to the floor plenum.

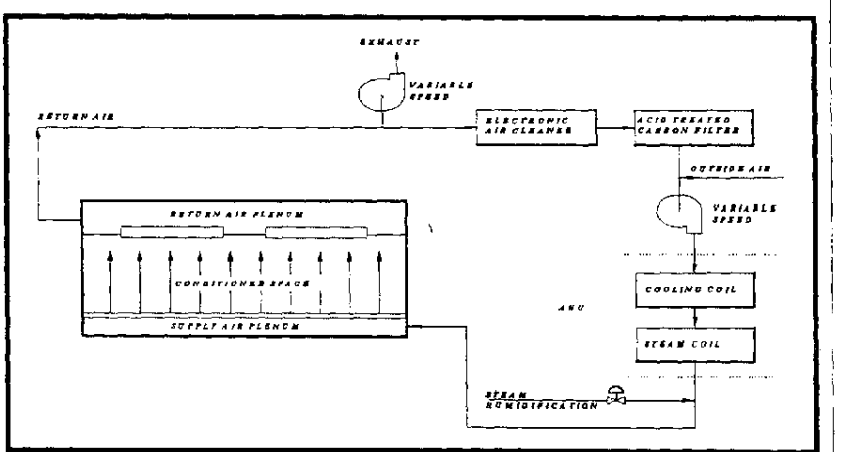

Figure 1: The upward plug flow ventilation system.

TEST ROOM

A room was set up at Philip Morris Research & Development, in Richmond, Virginia, to test the performance of the system. The 14 ft (4.27 m) x 14 ft (4.27 m) x 11 ft (3.35 m) room had a circulation rate of 1,800 ft^3 per minute (f^3/m), 850 litres per second (l/s) and 50% outside air. Concentrations of particulates were measured during and after a simulation with a thermal and particulate load equivalent to 24 people continuously smoking for five minutes.

Figure 2 illustrates the performance of the system, comparing concentrations in the part of the room where people breathe – about 1.7 m above floor level – with calculated results for a conventional mixed room under similar conditions.

The levels of particulates in the breathing zone of the conventional room increased to a much higher level, and remained considerably higher for a longer period of time, than they did in the plug flow room. This suggests that the breathing zone in a properly-designed upward plug flow ventilation system contains significantly lower concentrations of particulates than that of conventional HVAC systems.

A second paper, entitled *Status of Research and Development Relating to Upward Plug Flow HVAC Technology*, was presented at last year's CORESTA conference. It described further experiments that have drawn similar conclusions.

Scientists, architects and engineers at Virginia Polytechnic Institute and State University at Blacksburg, Virginia, carried out experiments to compare the thermal and air quality performance of upward plug flow ventilation technology with that of conventional HVAC technology.

The research, funded by Philip Morris USA, also aimed to include standard HVAC measurements of indoor air quality and to contribute to the development of models and methods for the design of commercial

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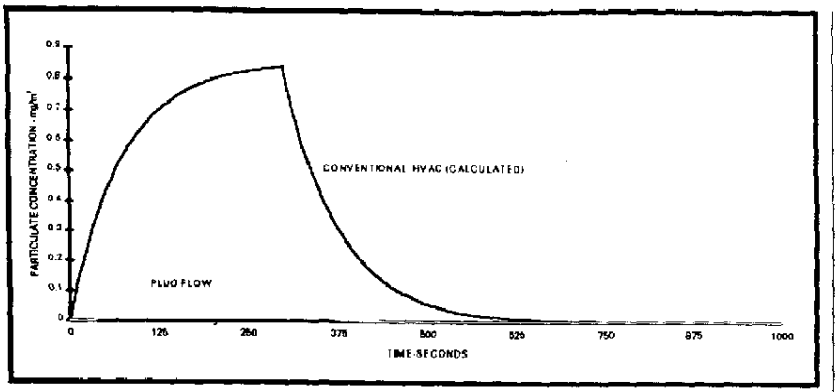

Figure 2: Concentrations of particulates were higher, for longer, in the conventional room than they were in the plug flow room.

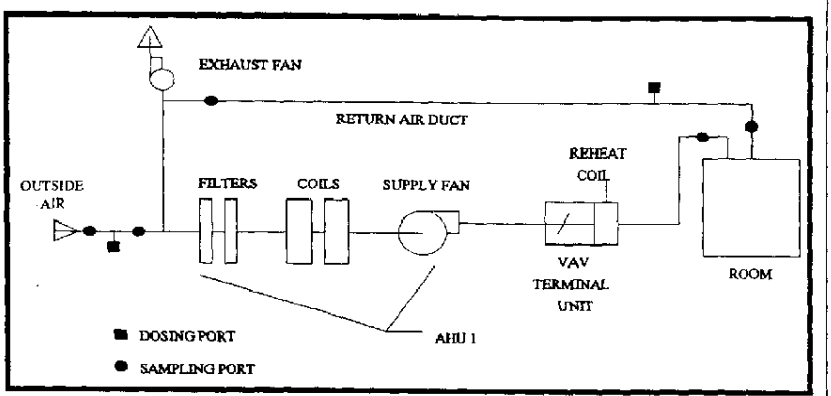

Figure 3: The conventionally air-conditioned room used this VAV system

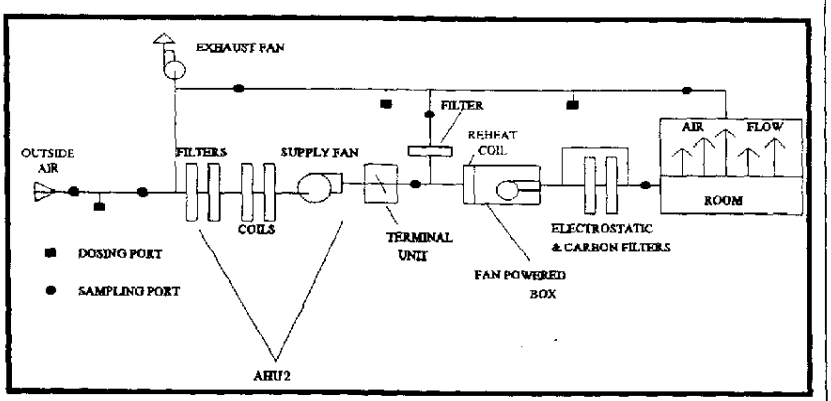

Figure 4: The VDV HVAC system used in the plug flow room.

facilities based on the plug flow ventilation concept.

Two identical offices, each containing 700 ft² (65 m²) of floor area, were built at the university, one conditioned by conventional variable air volume (VAV) HVAC technology and the other by the upward plug flow technology – or vertical displacement ventilation (VDV). Both rooms had 9 ft (2.7 m) acoustic tiled ceilings and raised floors and were designed for a summer indoor temperature of 76° F and a winter indoor temperature of 72° F, as measured by a thermometer exposed to the air-water-vapour mixture in the room.

In the conventionally conditioned room, shown in figure 3, supply air enters the room via ceiling diffusers and exits through return grilles around the lights. Outside air is conditioned by air handling unit number 1 (AHU 1) and a VAV reheat terminal unit, which is a device that maintains temperature by varying the volume and temperature of conditioned air delivered to the room. This unit contains an internal damper and heating coil and is controlled from a thermostat located in the conditioned space. AHU 1 was designed with a 35% efficiency filter with provisions for a future 85% efficiency filter. Figure 3 also shows the locations of sampling and dosing ports.

The upward plug flow room used virtually the same system as that used in the earlier simulation room in Richmond. The VDV room, shown in figure 4, is conditioned with supply air via a perforated raised floor covered with specially-backed commercial woven carpet. Room air is sent into return air grilles in the ceiling. Outside air is conditioned by air handling unit number 2 (AHU 2), designed with both 35% and 85% efficiency filters mounted in series. AHU 2 provides supply air to a terminal unit similar to the one used for the VAV HVAC system, except that this unit does not include a reheat coil.

RECIRCULATION AIR

Air from this unit mixes with recirculation air and then passes over a reheat coil into a fan-powered mixing box, which then provides a constant volume of air to the room. The room was equipped with electrostatic and carbon filters, similar to the original simulation room, but these filters were bypassed for the testing described here. The recirculation air duct includes a high efficiency filter.

Each room was ventilated with approximately equal volumes of outside air during the evaluation. The total supply air for the VAV room consisted of 725 f^3/m outside air and 25 f^3/m of recirculation air, totalling 750 f^3/m, with 97% make-up air. Supply air for the VDV room consisted of 788 f^3/m outside air and 1,162 f^3/m of recirculation air – a total of 1,950 f^3/m, with 40% make-up air.

THERMAL LOAD

The VAV and VDV rooms were evaluated at low and high levels of heat – or thermal load. The low load was simulated using the overhead lighting and one person seated in the middle of the test rooms as the only internal heat sources. This produced approximately 12 W/m² of thermal load.

The high thermal load, representing the heat produced by nine people and nine computers, was simulated using electric blankets folded to approximate a person's surface area, and ventilated boxes, each containing two 75 W light bulbs, to simulate the computers. These simulated loads, together with the overhead lights and one person sitting in the centre of the test rooms, produced approximately 44 W/m² of thermal load.

Gaseous contaminants in each room were simulated by sulphur hexaflouride, SF_6. Six continuously-burning cigarettes generated particulate matter, volatile organic compounds (VOCs[5]), CO and CO_2. The

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cigarettes and tracer gas dosing tubes were located 0.9m above floor level. The person sitting in the room also acted as a source of CO_2 and particulates. Additional SF_6 dosing ports were located in the HVAC systems as shown in figures 3 and 4.

Three sampling locations were established in each room, in the middle, in the corner, and halfway between the centre and the corner. At each location, samples were taken at five heights above the floor: 0.1 m, 0.6 m, 1.1 m, 1.7 m, and 2.5 m. The 1.1 m and 1.7 m heights correspond to typical breathing locations for seated and standing individuals, respectively.

Figure 5 shows the locations of the sampling points and heat sources within the two rooms. Additional sampling points were located in the HVAC ductwork, as shown in figures 3 and 4.

For the tests, the room ventilation, SF_6 dosing, and thermal loads were applied until the system reached steady state. Measurements and samples of CO_2, CO, TVOC, SF_6, H_2O, particulates, temperature, air velocity, and air turbulence, were then taken throughout the system to characterise air quality.

CONCENTRATIONS

Outside air was monitored to determine the background concentrations of CO_2, CO, and TVOC, before beginning the tests, between each test, and on completion of the tests. The background concentrations were found to be relatively low and stable with the exception of CO_2. Background readings for CO and TVOC were within the precision of the gas analyser for each gas. Thus, a value of zero was chosen to best represent the supply air concentrations of CO and TVOC. The background levels of CO_2 were higher and less stable than the other parameters. A mean value of 344 parts per million (ppm) was, therefore, chosen for CO_2. Because the test facility is close to agricultural land, supply and outside air will be simultaneously monitored in future.

BREATHING ZONE

The most appropriate way of comparing VDV HVAC technology with conventional mixed air systems is to look at absolute concentrations of substances in the breathing zone.

The researchers compared the concentrations of TVOC, SF_6, and particulates at a certain height above the floor, in both low load and high load conditions. They found considerably lower contaminant concentrations in the occupied zone for the VDV room. The data also illustrates that VDV technology results in two distinct zones within the room. The lower, occupied zone, reaching to 1.7m above floor level, is an unmixed, clean zone, with vertical plug flow air movement and uniformly low concentrations of contaminants.

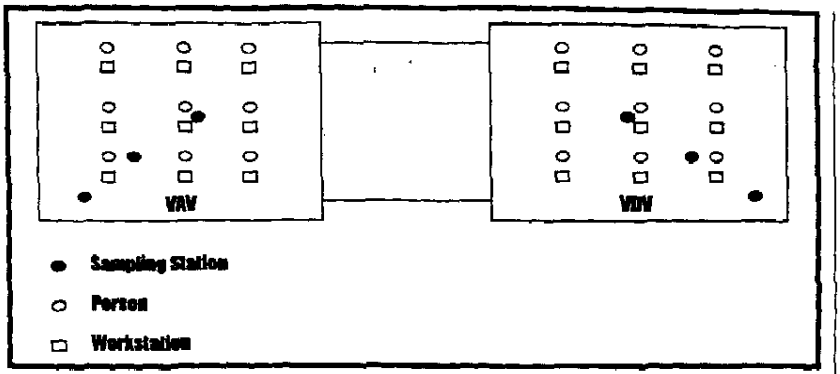

Figure 5: Electric blankets were used to simulate people and lightbulbs were used to simulate the heat produced by their computers.

The upper, dirty zone, from 2.5m above floor level, is fully mixed with near-uniform temperature distribution and considerably higher contaminant concentrations. Contaminants introduced into the lower zone do not mix or spread laterally, but rise vertically into the upper dirty zone. Contaminants introduced directly into the upper zone mix with the turbulent air flow in that zone but do not recirculate or mix with the lower, clean zone.

SF_6 concentrations as a function of height clearly show that the interface between the clean and dirty zones for the VDV room is between 1.7m and 2.5m for both low and high thermal load conditions. The very low particulate concentrations in the VDV room were a result of both the ventilation pattern in the room and the high efficiency filter located in the recirculation ductwork.

Figure 6 summarises the measured concentrations of CO_2, CO, TVOC, SF_6, and particulates for high and low

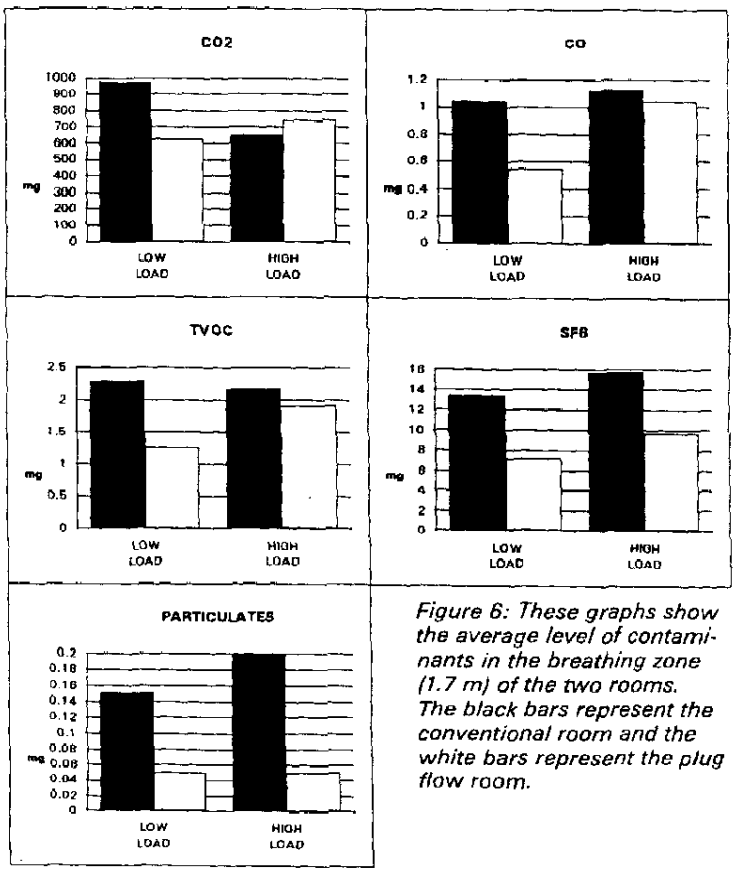

Figure 6: These graphs show the average level of contaminants in the breathing zone (1.7 m) of the two rooms. The black bars represent the conventional room and the white bars represent the plug flow room.

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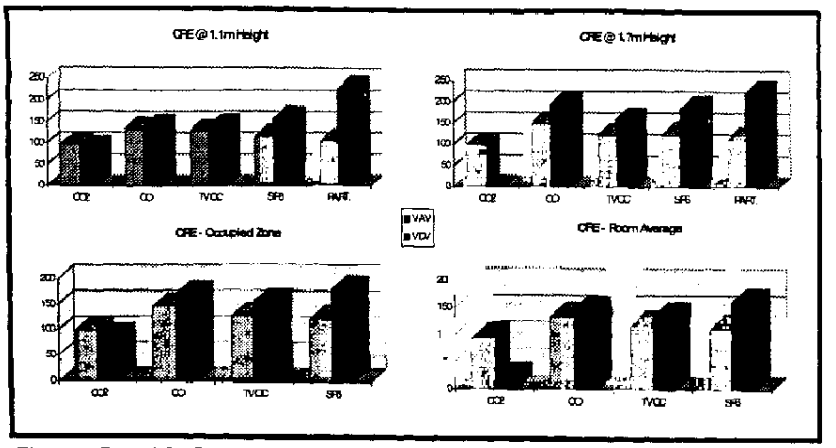
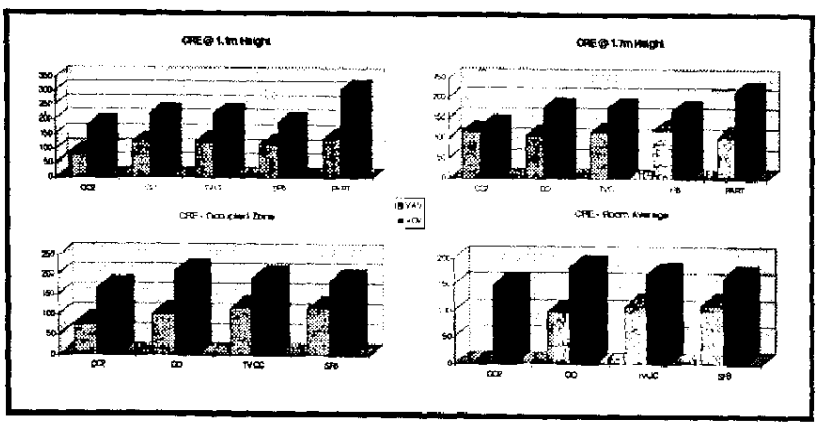


Figures 7 and 8: Contaminants in the VDV (plug flow) room (indicated by the second of the bars of each pair) were removed more effectively than were those in the VAV room. This happened at both a high thermal load (above) and at a low thermal load (below).



load conditions for the VDV and VAV rooms.

Contaminant removal effectiveness (CRE) is a standard HVAC measure of how effectively certain substances generated in the occupied space are removed and prevented from spreading in the occupied space.

It is defined as:

$CRE = 100\% (C_e - C_s) / (C_1 - C_s)$

where:

C_e = contaminant concentration in the room exhaust air

C_s = contaminant concentration in the supply air

C_1 = contaminant concentration at the sample point.

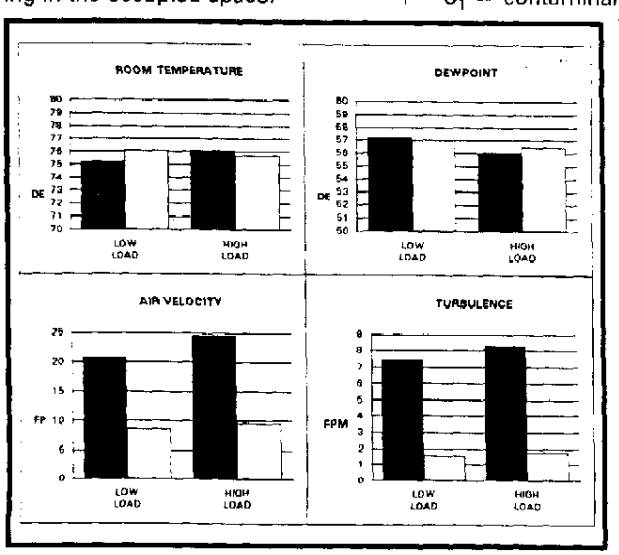


Figure 9: Measurements taken in the breathing zones of the VAV (black bars) and VDV (white bars) rooms.

Figure 7 compares contaminant removal effectiveness (CRE) for CO_2, CO, TVOC, SF_6, and particulates at the high thermal load condition for the VAV and VDV rooms. Results are calculated based on the measured concentrations at the 1.1 m and 1.7 m heights as well as on the room average and occupied average.

The VDV room shows consistently higher contaminant removal effectiveness than the VAV room. Figure 8 reflects similar results under low thermal load conditions.

The study also showed that occupants of the VDV room were less likely than those of the VAV room to say they were made uncomfortable by draughts. This is shown by the figures for Percent Dissatisfied (PD), another standard HVAC term that estimates the proportion of the occupants who are uncomfortable.

PD is calculated as:

$(34 - t_{a,a}) (v_a - 0.05) 0.62 (0.37 SD_v + 3.14)$ where:

$t_{a,a}$ = average test zone air temperature (°C)[9];

v_a = mean air velocity (m/s);

SD_v = standard deviation of air velocity (m/s).

ACCEPTABLE VALUES

PD values of less than 15% are acceptable, according to the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE). Based on this criteria, the individual measurements of PD for all sampling locations were examined.

Figure 10 shows the results of the PD calculation based on measured temperatures and air velocities under both low and high simulated load conditions for the VAV and VDV rooms. Calculations were made for the occupied zone and for the entire room. All measured sampling points met the criteria for the VDV room under both low and high loadings.

These excellent results indicate that VDV HVAC technology provides uniform supply air diffusion through the room's entire floor surface area, resulting in significantly reduced air velocities without a reduction in total air supplied to the room.

In the VAV room, however, several points did not meet the ASHRAE criteria because PD was more than 15%, as reflected in the lower acceptability percentages. Figure 9 shows air velocity and turbulence measurements in the breathing zone, along with room temperature and dewpoint.

ZONES

Design is a major issue in upward plug flow HVAC technology. The interface between the clean and dirty zones must be well above the occupants' heads, and this largely depends on the shape and size of the room and the rate of air supply.

A researcher, Makoto Koganei, developed a model which predicts the height of this interface in a variation of plug flow using diffusers located around the perimeter of the room, just

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	VAV		VDV	
	Occupied Zone	Room	Occupied Zone	Room
Low Load	7.3%	7.0%	0.6%	0.7%
High Load	9.6%	9.1%	0.5%	0.5%

Figure 10: The average Percent Dissatisfied – or the proportion of room occupants who complained of draughts – was far lower in the VDV room.

above the floor. The model is based upon plug flow in the clean zone and uniform mixing in the dirty zone. There is no recirculation between the zones except via heat source plumes.

Koganei's model assumes that in VDV systems, a warm air zone is formed in the upper part of the room by the thermal plumes generated by heat sources in the space, as shown in figure 11. The warmer air does not descend below a certain level, because of its lower density.

Koganei's model includes empirically-determined coefficients based on experimental data obtained with this type of ventilation geometry. We believe that a similar approach will be applicable to systems similar to the VDV room using ventilation through the perforated floor. Additional work to develop data at various supply air flows should permit the derivation of engineering design criteria for these systems.

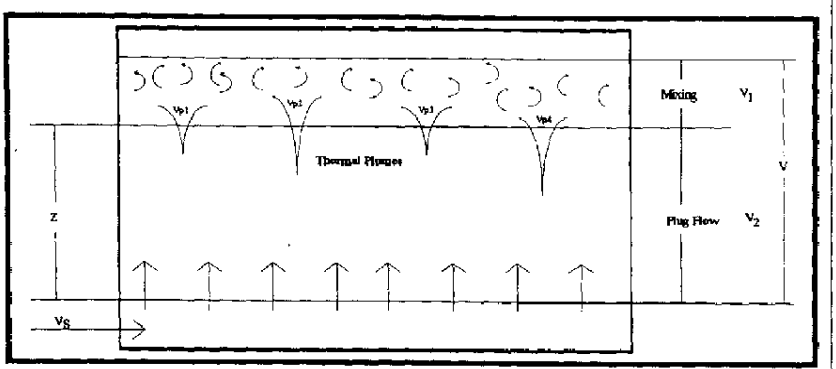


Figure 11: A warm air zone is formed in the upper part of the room by thermal plumes created by heat sources.

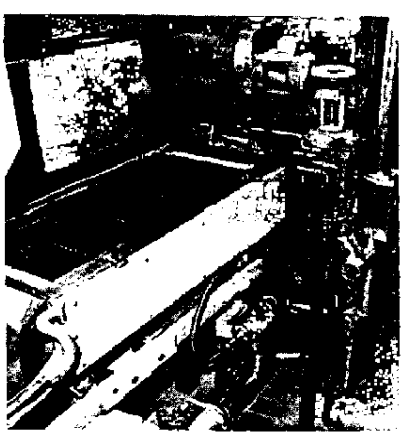
CONCLUSION

The data, then, show that breathing zone contaminants can be significantly reduced without making a room's occupants uncomfortable and without increasing the amount of outside air. The VDV system provides greater air quality and comfort than does the VAV configuration, in which, as the thermal load increases, so do the concentrations of contaminants, while the thermal comfort lessens.

In the VDV system, there are consistently lower contaminant concentrations in the occupied zone, and significantly lower air velocities and turbulence lead to greater comfort, even with an increase in the thermal load. This system of ventilation provides a lower clean zone by concentrating contaminants in the upper part of the room, above the occupied space.

Harold Burnley is director of process development and Leonard Lipscomb is a research engineer at Philip Morris USA, Research & Development, Richmond, Virginia.

Steam Expansion and Drying System



1 Expansion and drying by steaming

On Line expansion takes place in a high efficiency steaming tunnel. Expansion of the tobacco cellular structure is achieved by the interactive transfer of three types of energy. Compression and thermal energy is activated and transferred at high speed to the tobacco, by the free jet system in the steaming tunnel. The moisture within the cells boils, and the resulting vapour pressure increase, expands the cellular structure and starts the drying process.

2 Drying by evaporative cooling

Following expansion, tobacco drying and cooling takes place in one cylinder. No additional heat energy is needed to dry the tobacco. Surplus steam is taken from the tunnel, and passed through a heat exchanger to produce drying air. This is introduced into the tobacco before the tunnel discharge, and as high speed vortices in the cylinder. The drying air combined with the high temperature of the tobacco, results in moisture reduction due to evaporation and rapid cooling

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